Response to Reviewers #2 Comments

We thank the associate editor, editor and two anonymous reviewers for their thoughtful and exhaustive comments and suggestions, which significantly help us to improve the quality of the manuscript. In this revised manuscript, we have revised the manuscript accordingly. Below, we indicate the original comment of the respective reviewer in blue and our point-to-point response is denoted in black.

Before addressing the comments, we would like to express our sincere gratitude to the reviewers for their exceptionally informative, constructive, and detailed comments.

Review report on the paper "Occurrence frequency of Kelvin Helmholtz instability assessed by global high-resolution radiosonde and ERA5 reanalysis" by Shao et al. submitted to the journal Amospheric Chemistry and Physics.

Overview This paper describes the spatial and temporal variability of instabilities in the atmosphere from a huge radiosonde (RS) database (115 million profiles (?) from 434 stations!). The resulting statistics from the radiosonde analysis are compared to those obtained from ERA5 reanalyses. The authors observe a severe underestimation of the vertical shear from ERA5. They find a better agreement between the instability climatology from RS and ERA5 by taking a threshold Ri < 1 when using ERA5. The authors also observe a positive correlation with the standard deviation of the orography. The analysis of the RS and ERA5 data is interesting and the climatological results seem very convincing. The comparison RS/ERA5 is also interesting. For these reasons, this work deserves publication. However, the interpretation of the results does not always seem to me to be correct. For instance, the fact of interpreting all instabilities detected from the Ri < 1/4 criterion as the result of Kelvin-Helmholtz instabilities is not justified, in particular in the boundary layer, or in the tropical troposphere. Therefore, substantial modifications seem to me necessary, if only the title.

I therefore recommend that this article be published with some substantial modifications.

Response: We sincerely appreciate the reviewers for their thorough and insightful comments and assessments, which have greatly benefited our present work as well as our future research. We learned a lot from your suggestive comments. In the following, we address your comments in detail, and we have revised some parts of our work based on your constructive suggestions, aiming to achieve your desired outcomes.

Major comments

1) lines 190-217: about the method for estimating the gradients from the HVRRS profiles. If I understand correctly, a moving average of the estimated gradients is performed over height segments of 200 m. But over what vertical scale are the gradients evaluated (which are then averaged)? Are they calculated over 10 m differences? If so, why this choice if one purpose is to compare with the estimates from ERA5? Why not estimate the vertical gradients of HVRRS on vertical scales comparable to the model (100-400 m) for comparison? Moreover, it would be simple to adapt the resolution of the HVRRS gradients to the resolution of the model according to the altitude domains considered.

Figure 1 is illuminating on that purpose in showing that the estimates of the occurrence frequency (OF) of Ri on a 100 m scale, without averaging, is little different from that estimated on 10 m differences averaged over 200 m.

Such a resolution (10 m averaged on 200 m segments) is relevant to establish the climatology of instability occurrences (Ri < 1/4) obtained from HVRRS, but is arguably questionable for comparison to the climatology deduced from ERA5.

Response: Very thanks for the comment. We totally agree with your assessment. In the revised version, we carried out the comparison based on two scenarios: (1) the comparison with 10-m radiosonde at all heights from near-ground up to 30 km; (2) the comparison with radiosonde at four specified height intervals with comparable vertical resolution. We hope these two versions of comparison could leave more spaces for readers.

In the updated files, Tables 2 and 3 illustrate the comparison of vertical wind shears and occurrence rate of low *Ri* at comparable vertical resolutions. The vertical resolution of radiosonde at 0.8–1.3 km, 2.2–3.2 km, 6–15 km, and 20–21 km a.s.l. was resampled to 100-m, 200-m, 300-m, and 400-m, respectively. The results suggest that even at a comparable vertical resolution, the vertical wind shear and $OF(Ri<1/4)$ in ERA5 reanalysis might be significantly underestimated. At these four height intervals, $0.5<Rit<1.5$ might be a more reasonable choice, rather than 1/4. In general, $Rit=1$ could be a proper choice for ERA5 reanalysis.

Accordingly, the related texts and tables has been added in the updated manuscript.

Table 2. The occurrence rate of low *Ri* at 0.8–1.3 km a.s.l. (a), 2.2–3.2 km a.s.l. (b), 6–15 km a.s.l. (c), and 20–21 km a.s.l. (d). The critical *Ri* (*Rit*) is 1/4 for radiosonde, and it increases from 1/4 to 2 for ERA5 reanalysis. Note that HVRRS data were vertically resampled to 100-m, 200-m, 300-m, and 400-m at these four height intervals to match with the ERA5 reanalysis. In addition, the moving average number in Eq.(1) is 0. RS stands for radiosonde.

(a) Frequency of low *Ri* at 0.8–1.3 km a.s.l. (%) / Vertical resolution of RS is 100-m							
	Polar (NH)	**Midlatitude (NH)**	**Subtropics (NH)**	**Tropics**	**Subtropics (SH)**	**Midlatitude (SH)**	**Polar (SH)**
RS, *Rit*=1/4	15.20	24.25	22.86	13.92	22.09	22.43	20.77
ERA5, *Rit*=1/4	2.55	8.88	6.37	2.19	6.80	4.47	2.94
ERA5, *Rit*=0.5	3.77	12.06	9.63	3.65	11.91	7.95	7.22
ERA5, *Rit*=1	8.54	21.22	20.48	8.27	25.45	18.21	15.78
ERA5, *Rit*=1.5	14.18	29.62	30.44	12.88	36.07	27.97	23.22
ERA5, *Rit*=2	19.44	36.58	38.32	17.20	43.72	36.00	29.68
(a) Frequency of low *Ri* at 2.2–3.2 km a.s.l. (%) / Vertical resolution of RS is 200-m							
RS, *Rit*=1/4	3.04	6.22	9.00	5.67	9.71	4.29	3.98
ERA5, *Rit*=1/4	0.24	0.60	1.00	1.30	2.26	0.26	0.1
ERA5, *Rit*=0.5	0.37	1.03	1.96	2.10	4.22	0.50	0.18
ERA5, *Rit*=1	1.16	3.26	6.35	5.20	10.00	2.20	0.91
ERA5, *Rit*=1.5	2.77	6.75	12.20	9.00	16.31	5.60	2.68
ERA5, *Rit*=2	5.02	10.85	18.05	13.03	22.45	9.84	5.10
(c) Frequency of low *Ri* at 6–15 km a.s.l. (%) / Vertical resolution of RS is 300-m							
RS, *Rit*=1/4	0.76	2.24	3.91	5.98	4.46	1.98	0.59
ERA5, *Rit*=1/4	0.10	0.38	0.54	1.46	0.56	0.24	0.05
ERA5, *Rit*=0.5	0.32	1.16	1.95	4.36	2.10	0.93	0.15
ERA5, *Rit*=1	1.37	4.33	7.72	13.14	8.89	3.51	0.61
ERA5, *Rit*=1.5	2.93	8.31	14.54	21.78	17.05	6.76	1.38
ERA5, *Rit*=2	4.70	12.35	20.91	29.28	24.55	10.02	2.32
(d) Frequency of low *Ri* at 20–21 km a.s.l. (%) / Vertical resolution of RS is 400-m							
RS, *Rit*=1/4	0.03	0.07	0.13	0.04	0.04	0.10	0.07
ERA5, *Rit*=1/4	0.01	0.02	0.01	0.02	0.02	0.03	0.04
ERA5, *Rit*=0.5	0.02	0.03	0.01	0.02	0.03	0.04	0.04
ERA5, *Rit*=1	0.03	0.05	0.04	0.05	0.05	0.08	0.04
ERA5, *Rit*=1.5	0.04	0.11	0.13	0.19	0.09	0.17	0.04

ERA5, *Rit*=2	0.05	0.21	0.32	0.55	0.18	0.30	0.05

Table 3. Vertical wind shears at 0.8–1.3 km a.s.l. (a), 2.2–3.2 km a.s.l. (b), 6–15 km a.s.l. (c), and 20–21 km a.s.l. (d). Note that HVRRS data was vertically resampled to 100-m, 200-m, 300-m, and 400-m at these four height intervals to match with the ERA5 reanalysis. RS stands for radiosonde.

(a) Wind shear at 0.8–1.3 km a.s.l. (m/s/km) / Vertical resolution of RS is 100-m							
	Polar (NH)	**Midlatitude (NH)**	**Subtropics (NH)**	**Tropics**	**Subtropics (SH)**	**Midlatitude (SH)**	**Polar (SH)**
RS	12.50	13.63	11.80	9.83	13.54	13.06	13.85
ERA5	5.43	5.92	6.47	4.83	7.02	6.71	6.05
(b) Wind shear at 2.2–3.2 km a.s.l. (m/s/km)/ Vertical resolution of RS is 200-m							
RS	8.31	9.09	9.24	9.08	9.45	9.39	10.00
ERA5	3.72	4.47	5.19	4.65	5.41	4.71	4.19
(c) Wind shear at 6–15 km a.s.l. (m/s/km) / Vertical resolution of RS is 300-m							
RS	8.30	9.50	9.41	7.72	9.80	9.38	8.00
ERA5	4.00	5.22	5.84	5.21	6.14	4.76	3.37
(d) Wind shear at 20–21 km a.s.l. (m/s/km) / Vertical resolution of RS is 400-m							
RS	9.02	10.40	11.67	12.56	12.14	10.48	9.80
ERA5	3.00	3.83	4.79	5.59	4.72	3.63	2.98

2) paragraph 3.2: The authors correctly note that the frequency of occurrence (OF) of KHIs depends on the vertical resolution of the gradients. The fact that the OFs from the model coincide better with those from the HVRRS with a threshold Ri < 1 is therefore fortuitous since it depends on the resolution of the HVRRS. (If you had calculated the gradients on a 50 m scale, and not 10 m, you would have lower OFs, and therefore a different threshold to apply on the model estimates).

Can you please comment on this fact?

Response: We agree. Since the thickness of turbulence in the free troposphere is about 200-m based on our previous studies, the moving average number for a 50-m gridded profile would be 4. The *OF*(*Ri*<1/4) for a 10-m resolution and 20 moving average number is generally comparable with that for a 50-m resolution and 4 moving average number (Figure 1 in the updated file). The moving average in vertical is crucial to inhibit the instantaneous convection, as stated in Section 2.3.

In addition, as stated above, based on your comment we carried out another comparison experiment (ERA5 and radiosonde have a comparable vertical resolution) and also found that *Rit* should be larger than 1/4.

3) The authors systematically attribute Ri < 1/4 occurrences to KH instabilities. This is certainly not always the case. Thus, the diurnal boundary layer is very probably close to a neutral static stability (Ri ~ 0) without having anything to do with KH instabilities. The same is true in the tropical troposphere, where deep convective cells develops up to about 15 km altitude. The Ri < 1/4 occurrences are most likely a signature of an unstable flow, but not that this instability is due to a KHI. I recommend that the authors modify the discussion and conclusion paragraphs accordingly.
As well as the title of the article.

Response: We totally agree with you, very thanks for the suggestion! Based on your comments as well as the suggestion from Reviewer #1, we changed the title to "Occurrence frequency of subcritical Richardson number assessed by global high-resolution radiosonde and ERA5 reanalysis". Accordingly, in the updated files, the *OF*(KHI) has been replaced with *OF*(*Ri*<*Rit*) throughout all texts and figures.

4) Horizontal winds measured under radiosonde at the scale of a few tens of meters are affected by the chaotic movements of the gondola due to the pendulum and to the balloon's own movements (see for example Ingleby et al., 2022, https://doi.org/10.5194/amt-15-165-2022 and references therein). A low-pass filter is applied to the HVRRS profiles to reduce these effects. This filtering should have an impact on the effective resolution of the wind measurements (which is much larger than 10 m). Although it is difficult to assess the impact of this filtering, I suggest that you discuss this fact.

Response: Thanks! We have included this discussion in Section 2.3. In addition, we would like to address that the moving average in Eq.(1) could offset the effect of chaotic movements, to some extent, based on the finding in Figure 1.

Specific comments

- line 155: 115 million HVRRS profiles??? Do you confirm?

Response: Very sorry we make a serious mistake. We totally misunderstood the word "million" in the context of English for a long time (We thought it means 10,000). This analysis went through several versions. At the beginning of the analysis, about 1.15

million radiosonde was adopted during years 2016-2022. And then, we removed all data on 2016 due to the filled storage of our device (Since ERA5 137 model level data needs huge storage and computation resources). We rechecked our radiosonde dataset during years 2017-2022, and found that about 0.95 million radiosondes have been adopted.

The following Linux terminal displays the total count of radiosonde profiles during years 2017-2022.

```
jian@LAPTOP-2ECIDBLP:/mnt/d/RS_all_10m$ find . -name "*-201[7-9]*"  | wc -l
449531
jian@LAPTOP-2ECIDBLP:/mnt/d/RS_all_10m$ find . -name "*-202*"  | wc -l
495860
```

- Line 233: a “tropospheric segment” from 2 to 8.9 km is chosen. Why this choice (if interested in the OF(KHI) in the 0-2 and 10-15 km height ranges?

Response: The study height interval is from the near-ground up to 30 km. Our primary motivation was to select two typical height intervals (0-2 and 10-15 km) for visualization.

In Section 3.4, we have changed the subtitle to “The dynamical environment of *OF*(*Ri*<*Rit*) in the free troposphere”. The extracted gravity waves at 2-8.9 km were to characterize the wave environment of *OF*(*Ri*<*Rit*) in the free troposphere.

- line 240 (Fig. 2): what is the vertical resolution of the shear estimates from HVRRS? Please, specify.

Response: In the updated files, we have stated that HVRRS-based wind shear is taken from Eq.(1), with a vertical resolution of 10-m.

- lines 259 & 282: Are the ERA5 shear estimates dramatically lower than the HVRRS estimates if the RS gradients are estimated with the same resolution as the model (i.e. 300 m for the 10-15 km altitude domain)?

Response: According to the information in Table 3 in the revised manuscript, under a comparable vertical resolution, ERA5-based wind shear at 6–15 km a.s.l. is underestimated by around 4 m/s/km. Moreover, the following statement has been inserted into the revised Section 3.2:

“…As illustrated in Table 3, even accounting for the fact that ERA5 has a comparable vertical resolution of radiosonde, wind shears in ERA5 reanalysis are still underestimated by around 51.9%, 50.7%, 44.5%, and 62.5% at 0.8–1.3 km, 2.2–3.2 km, 6–15 km and 20–21 km a.s.l., respectively…”

Moreover, In Conclusion section, one paragraph has been added:

“However, the vertical resolution of ERA5 reanalysis sharply decreases with altitude, which is not comparable with HVRRS. Thus, to match with ERA5 reanalysis at specified height intervals, the HVRRS was vertically interpolated with resolutions spanning from 100-m to 400-m. Even at a comparable resolution, vertical wind shear is underestimated by around 50%, leading to a considerable underestimation in *OF*(*Ri*<1/4), compared to radiosondes. ”

- line 306: I agree with the statement that PBL is mixed by convection during daytime. Clearly, the occurrence of Ri < 1/4 is not attributable to KH instabilities in such cases.

Response: We agree. The mean *OF*(0<*Ri*<*Rit*) in ERA5 reanalysis 0–2 km a.s.l. is significantly lower than that of *OF*(*Ri*<*Rit*) (Figure S5a and Figure 9a). Around 40% of *OF*(*Ri*<*Rit*) can be attributed to *OF*(*Ri*<0) (Figure 8).

In addition, the related content has been modified correspondingly.

- line 376: this statement is not visible in figure 9.

Response: The statement has been removed, thanks.

- lines 381-3: I doubt that the Ri < 1/4 occurrences are only due to KHI in this region where deep convective cells are frequent.

Response: Yes. The percentage of *OF*(*Ri*<0) relative to *OF*(*Ri*<*Rit*) in the PBL is around 45%. We have added Figure 8 to illustrate the contribution from *Ri*<0, which is likely related to deep convective cell.

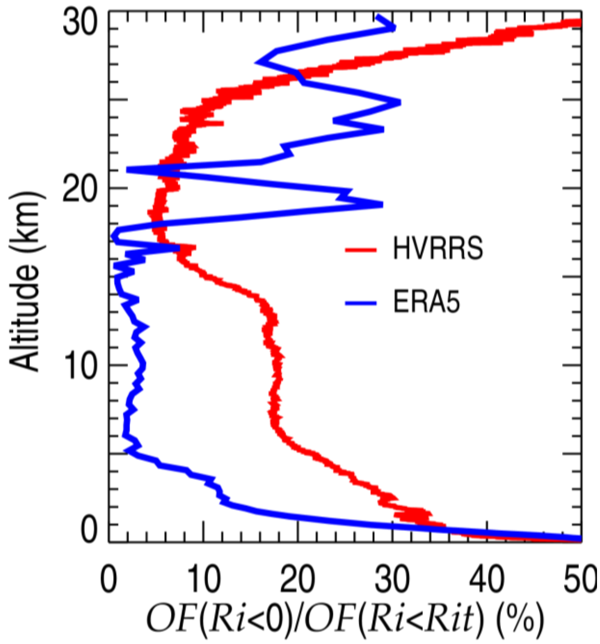

Figure 8. The percentage of *OF*(*Ri*<0) relative to *OF*(*Ri*<*Rit*) in HVRRS (red) and ERA5 reanalysis (blue).

- lines 414 & 793: la Niño → la Niña

Response: Amended.

- line 436: I do not understand your concluding sentence, figure 14b showing precisely that the probability of occurrence Ri < 1/4 depends almost not on the total energy of the gravity waves, but almost exclusively on the horizontal wind shear (if it exceeds 18 m/s/km).

Response: Figure 14 was intended to investigate the gravity wave characteristics of *OF*(*Ri*<*Rit*). For a clearer presentation, we calculated the distribution of *OF*(*Ri*<*Rit*) categorized by GW total energy, which is illustrated as Figure S9 in the revised supporting information. The *OF*(*Ri*<*Rit*) obviously statistically increases with GW total energy.

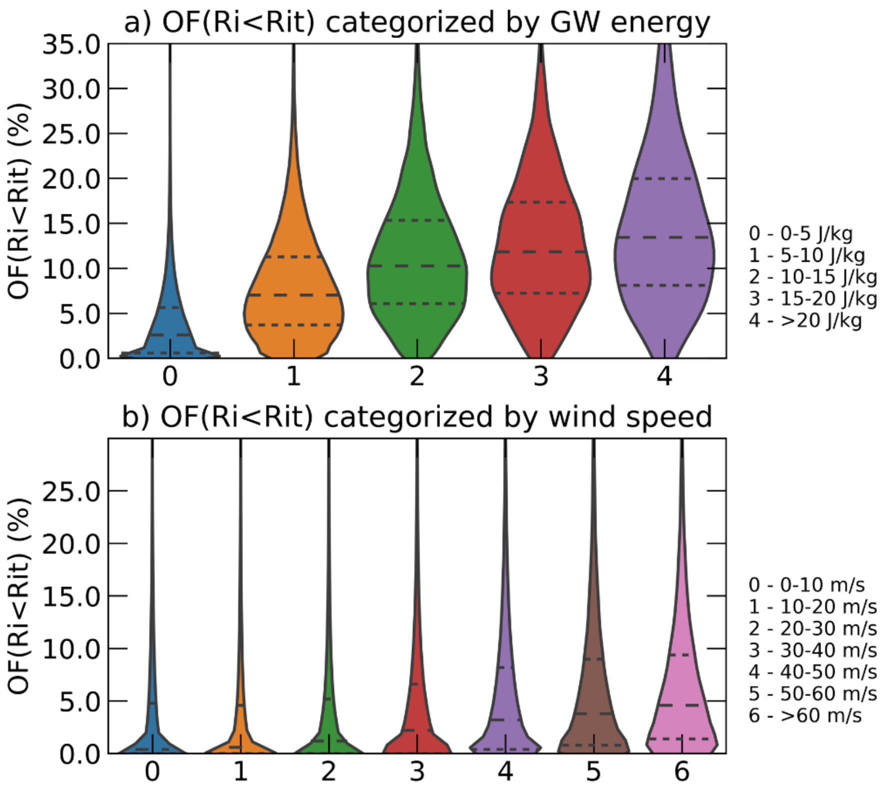

Figure S9. Violin plot of *OF*(*Ri*<*Rit*) categorized by GW total energy (a) and wind speed (b).

- line 443-456: I do not understand your conclusion about the wind speed. Figure 15 clearly shows that the occurrence Ri < 1/4 does not depend on the wind speed (if the wind speed exceeds a few m/s), but occurs with high probability if the shear exceeds ~20 m/s/km. This is a convincing result!

Response: Many thanks for the comment. The motivation of Section 3.4 was to investigate the association of GWs and mean flows with *OF*(*Ri*<*Rit*) by enhancing wind shears, as stated in the first paragraph of Section 3.4. As stated above, we also investigate the distribution of *OF*(*Ri*<*Rit*) categorized by wind speed. The result in Figure S9b indicates that the *OF*(*Ri*<*Rit*) also almost linearly increases with wind speed.